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Investigation of the potential of wind–waves as a renewable energy resource: by the example of Cesme—Turkey

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Abstract

There are opinions claiming that 70% of the world energy consumption could be provided from renewable resources by the year 2050. These resources are needed, because fossil fuels both cause pollution of the environment and will be depleted in the near future. In this regard, the objective of this study was to determine the wave energy potential and the costs associated with its application to Turkish waters. To this goal, the wave energy potential in Cesme–Izmir was investigated. Cesme is known to have abundant wind, which plays the primary role in the formation of sea waves. For this purpose, the Solar Energy Institute of Ege University carried out wind velocity measurements within the period from 05.11.1998 to 05.11.1999 at an altitude of 10 m in Cesme. The measured values were regarded as if they were taken at an altitude of 19.5 m from seawater level. With this approach, the Pierson–Moskowitz wave energy spectrum was constructed. Through this wave energy spectrum, wave energy that is to be obtained at the measurement area within one year was determined. The variation of wave energy according to each month was evaluated. Hence, the unit cost of electricity to be produced by a turbine (with a width of 1 m), assumed to be installed at the area of measurements, was calculated.

Keywords: Energy; Renewable energy; Sea sources; Wave mechanics; Wave energy

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1. Introduction

According to a classification, in which the existence period of the earth is taken as the reference, energy sources can be investigated in two groups as renewable energy sources and unrenewable ones.

Regarding the main source of the energy, renewable energy sources can be investigated in three groups as solar-sourced, earth-sourced, and moon-sourced. As will be seen from Table 1, the wind energy that is solar-sourced causes both the air movements in the atmosphere and the wave motions in the seas as the result of the natural energy transformation. This kinetic energy could be transformed to electrical energy by wind and wave energy plants.

Increases in the human population and in technological improvements have brought forward the demand for more energy and especially for electrical energy, since it has a wide area of application. This demand is satisfied from various resources depending on the technological characteristics of the countries. The resources which were used in the total electrical energy production of Germany in 1997 can be given as an example: nuclear energy: 31%, mineral coal: 26%, lignite: 25%, natural gas: 9%, hydraulic energy: 4%, wind energy: 0.5%, others: 4.5% [1]. However, Turkey obtained its electrical energy production in 1998 from the following sources: fuel oil: 6.6%, diesel oil: 0.3%, mineral coal: 2.7%, lignite: 29.5%, natural gas: 22.4%, LPG: 0.2%, naphtha: 0.1%, geothermal energy: 0.1%, hydraulic energy: 38%, and others 0.1% [2]. From these data, one can conclude that fossil fuels have an important place in the energy production of both countries, and that Germany additionally makes use of nuclear energy to a great extent. Both energy sources have their own problems, which directly affect all human beings. The first of these problems is that Uranium, which is the source of the nuclear energy, will be depleted in 50 years, whereas petroleum in 44 years, natural gas in 64 years, and coal in 185 years [1,3]. Another problem related to fossil fuels and nuclear energy is the harm that is inflicted on the environment by the use of these resources. However, 1 kW h of wave electricity prevents the emission of 750–1250 g CO_2, 40–70 g ashes, 5–8 g SO_2, 3–6 g NO_x [2]. For these reasons and in order to meet the energy demand in recent years, there is a tendency to utilize the environment-friendly

Table 1
Classification of the renewable energy sources

Renewable energy sources				
Main source	Primary energy sources	Natural energy transformation	Technical energy transformation	Usable energy
Sun	Water	Evaporation, rain, etc.	Water power plants (hydroelectric plants)	Electrical energy
	Wind	Air motion in the atmosphere	Wind energy plants	Electrical and mechanical energy
		Wave motion	Wave energy plants	Electrical and mechanical energy
	Sunlight	Heating of the earth and the atmosphere	Heat pumps	Heat energy
		Sunlight	Collectors	Heat energy
			Solar cells (photo voltaic)	Electrical energy
	Biomass	Biomass production	Heat power plants	Heat and electrical energy
			Transformation plants	Fuel energy
Earth	Earth center's heat	Geothermal energy	Geothermal power plants	Heat and electrical energy
Moon	Moon attraction force of gravity	Tides	Tidal power plants	Electrical energy

renewable energies such as wind, solar, wave, geothermal, biomass, tidal and hydraulic energies.

The movements of the sea surface caused by external effects like wind, submarine earthquakes, marine vehicles or attraction of gravity of the moon and sun are called "sea waves". Sea waves due to the wind are more continuously compared to sea waves formed by other effects and therefore, they are considered primarily in obtaining energy.

Wave energy potential, as it is found in nature, is called natural potential. Technical potential is the transformed form of the natural potential to usable energy by technological systems. The economic potential is the economically defined amount when compared to the other energy sources. Table 2 states that the earth's sea-sourced natural energy potential is higher than the natural potential of the hydraulic and biomass energies together, and furthermore around 25% of the natural potential of wind energy.

In the literature, there are opinions claiming that 70% of the world energy consumption could be provided from renewable resources by the year 2050 [1]. As shown in Table 3, the annual wave energy natural potential and technical potential of Turkey are predicted to amount to 150 and 18 billion kW h, respectively [4]. When it is considered that the annual electrical energy production of Turkey in 1998 was around 111 billion kW h, one can conclude that wave energy in production of the electrical energy is the source that should first be resorted to in Turkey.

It should be noted that some estimations and predictions related to wave energy potential depend on certain assumptions and these assumptions are always open to discussion. More realistic determination of wave energy potential requires the making of expensive measurements to be executed for years at the area where the wave energy will be utilized. In cases where these measurements cannot be carried out, wind measurements, which are more economical, are accomplished. The wave energy can be calculated by using semi-empirical formulae relating the wind and wave. These formulae were obtained from numerous measurements of the wind. The amount of the wave energy calculated in this way is used to estimate the electrical energy that will be produced by the wave turbine(s) located at the area of measurements.

In this study, the wave energy potential at an area in Cesme–Izmir was determined. Cesme is known to have abundant wind, which plays the primary role in the formation of sea waves. For this purpose, the Solar Energy Institute of Ege

Table 2
Annual renewable natural energy potential of the world

Solar-sourced energy	Solar energy	Wind energy	Sea-sourced energy	Hydraulic energy	Biomass energy
Potential of the world (billion kW h)	1 524 240 000	30 844 000	7 621 000	46 000	1 524 000

Table 3
Annual renewable potential energy of Turkey

Classification of renewable energy	Usage kind of energy	Natural potential	Technical potential	Economical potential
Solar energy	Electrical energy (billion kW h)	977 000	6105	305
	Heat (mtep)	80 000	500	25
Hydraulic energy	Electrical energy (billion kW h)	430	215	124.5
Wind energy				
Direct terrestrial	Electrical energy (billion kW h)	400	110	50
Direct maritime	Electrical energy (billion kW h)	–	180	–
Sea wave energy	Electrical energy (billion kW h)	150	18	–
Geothermal energy	Electrical energy (billion kW h)	–	–	1.4
	Heat energy (mtep)	31 500	7500	2843
Biomass energy	Fuel (classic) (mtep)	30	10	7
	Fuel (modern) (mtep)	90	40	25

University carried out the measurements of wind velocity within the period from 05.11.1998 to 05.11.1999 at an altitude of 10 m in Cesme. The measured values were regarded as if they were taken at an altitude of 19.5 m from seawater level. With this approach, the Pierson–Moskowitz wave energy spectrum was constructed. Through this wave energy spectrum, wave energy that is to be obtained at the measurement area within one year was determined. The variation of wave energy according to each month was evaluated.

Whereas the wave turbines can utilize three quarters of the total wave energy in deep water, in this study, it was assumed that the wave energy reaches the turbine without any loss. Because nearly all of the wave energy in shallow water, like off Cesme's shore, could be transmitted and used in the direction of the turbine [5]. Hence, the unit cost of the electricity to be produced by a turbine with a width of 1 m, assumed to be located at the area of measurements, was calculated.

2. Material and method

The results of the wind velocity measurements carried out by the Solar Energy Institute of the Ege University within the period from 05.11.1998 to 05.11.1999 at an altitude of 10 m in Cesme are presented in Table 4 in the form of monthly averages. These measurements were started on 05.11.1998 at 18:30 and completed on 05.11.1999 at 18:20. The data were taken at the end of each 10-s period, and averages of every 10-min period were recorded. Within one year's time 52 560 10-min periods were obtained. The annual average wind velocity, at the measure-

Table 4
Calculation of energy spectrum on 08.11.1998 between 20:00 and 20:10 for the average wind velocity $V_w = 10.5$ m/s.

ω (rad/s)	$S_{\zeta\zeta}(\omega)$ (m^2s)	Simpson's coefficients (SC)	$S_{\zeta\zeta}(\omega)$ (SC)	ω (rad/s)	$S_{\zeta\zeta}(\omega)$ (m^2s)	Simpson's coefficients (SC)	$S_{\zeta\zeta}(\omega)$ (SC)
0.2	0.0000	0.5	0.0000	1.7	0.0513	2	0.1026
0.3	0.0000	2	0.0000	1.8	0.0391	1	0.0391
0.4	0.0000	1	0.0000	1.9	0.0302	2	0.0604
0.5	0.0030	2	0.0060	2.0	0.0235	1	0.0235
0.6	0.1293	1	0.1293	2.1	0.0185	2	0.037
0.7	0.4431	2	0.8862	2.2	0.0148	1	0.0148
0.8	0.6006	1	0.6006	2.3	0.0119	2	0.0238
0.9	0.5590	2	1.118	2.4	0.0096	1	0.0096
1.0	0.4436	1	0.4436	2.5	0.0079	2	0.0158
1.1	0.3293	2	0.6586	2.6	0.0065	1	0.0065
1.2	0.2387	1	0.2387	2.7	0.0054	2	0.0108
1.3	0.1723	2	0.3446	2.8	0.0045	1	0.0045
1.4	0.1252	1	0.1252	2.9	0.0038	2	0.0076
1.5	0.0918	2	0.1836	3.0	0.0032	0.5	0.0016
1.6	0.0682	1	0.0682			Total	5.1602

ment area at an altitude of 10 m, was determined as 6.24 m/s. As can be seen from Fig. 1, Cesme possesses a very high potential of wind and wave energy in the five-month period from October to February, during which the demand for energy is higher than other months. Certainly, Cesme has a high-energy potential of wind and wave during the other seven months also.

The wave energy, which will be transformed to another usable form of energy by the wave energy plants, is defined as the energy per unit surface area of the sea $\bar{E}$.

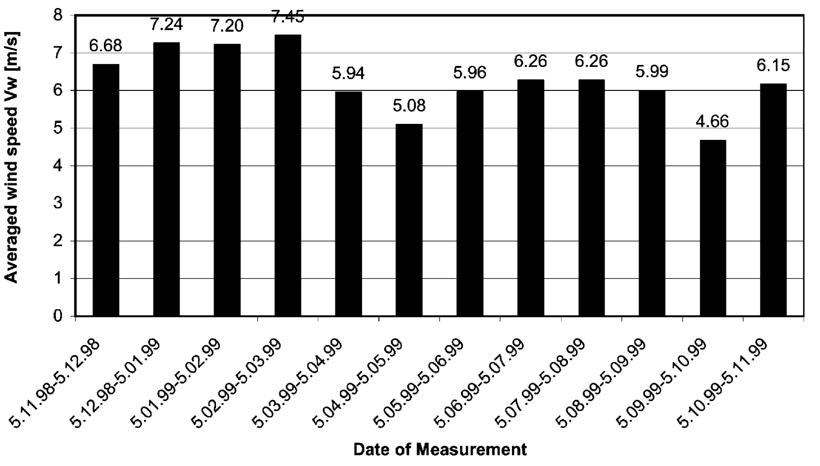

Fig. 1. Averaged wind velocity measured monthly at an altitude of 10 m in Cesme.

This energy is found by integrating the wave energy spectrum function $S_{\zeta\zeta}(\omega)$ over the entire frequency range and by multiplying the density of the seawater. In this connection, the wave energy spectrum function $S_{\zeta\zeta}(\omega)$ defines the distribution of wave components according to the frequency.

$$\bar{E} = \gamma_{sw} \cdot \int_0^\infty S_{\zeta\zeta}(\omega)\,\mathrm{d}\omega \ [\mathrm{Nm/m^2 \ or \ Ws/m^2}] \tag{1}$$

In Eq. (1), the density of seawater is taken to be $\gamma_{sw} = 10\,250\ \mathrm{N/m^3}$ and the wave energy spectrum $S_{\zeta\zeta}(\omega)$ is defined in terms of the wind velocity as semi-empirical relations, which were derived from numerous measurements [6]. The most frequently used relation of the wave energy spectrum is the Pierson–Moskowitz wave energy spectrum, which was derived for a fully developed sea in the North Atlantic Ocean.

$$S_{\zeta\zeta}(\omega) = \frac{8.1g^2}{\omega^5}10^{-3}\mathrm{e}^{-0.74(g/\omega V_w)^4} \ [\mathrm{m^2 s}] \tag{2}$$

In Eq. (2), the gravitational acceleration is taken to be $g = 9.81\ \mathrm{m/s^2}$, V_w denotes the wind velocity in m/s, and ω denotes the angular wave frequency in rad/s, and the unit of the wave energy spectrum $S_{\zeta\zeta}(\omega)$ becomes $\mathrm{m^2s}$. As can be seen from Eqs. (1) and (2), in order to calculate the wave energy per unit sea surface area, the wave energy spectrum should be determined and integrated over the whole angular frequency range from zero to infinity for every wind velocity measured. However, in practice, angular frequencies within the range of 0.2–3 rad/s contribute to the wave energy per unit surface area. The wave energy calculated at natural angular frequencies outside this range comes out to be small so that it can be neglected. In this study also, the frequency range of $\omega = 0.2$–3 rad/s will be considered. The integration in Eq. (1) will be carried out numerically by using the Simpson's method.

In obtaining electrical energy by using wave turbines, the most important parameter is the energy transmission, namely the wave power. Denoting the width of the wave by b, the wave power is given by [6]:

$$P = \bar{E}bC_g \ [\mathrm{W}] \tag{3}$$

In Eq. (3), C_g denotes the velocity of the wave group consisting of waves with the same wavelength, and for shallow water, C_g is given by:

$$C_g = \sqrt{gd} \ [\mathrm{m/s}] \tag{4}$$

In Eq. (4), d is the water depth given as $d = 10$ m, for which the wave energy potential is to be determined. For the calculation of the energy that will be delivered by the wave to a body with a width of b, the wave power obtained by Eq. (3) should be multiplied with Δt, which is the "duration of effect".

As an example for the method explained here, the energy spectrum calculation with the data on 08.11.1998 between 20:00 and 20:10 is presented in Table 4. The average wind velocity during this 10-min period was $V_w = 10.5$ m/s. The integral in the calculation of the wave energy affecting unit surface area in Eq. (1) is

determined numerically by Simpson's method. In this study, the angular frequency interval is taken as $\Delta\omega = 0.1$ rad/s. As a result in the 10-min duration, the wave energy affecting unit surface area is found as follows:

$$\bar{E} = \gamma_{sw} \cdot \int_0^\infty S_{\zeta\zeta}(\omega)\ d\omega = \gamma_{sw}\frac{2}{3}\Delta\omega(\mathrm{TOTAL}) = 10250\frac{2}{3}(0.1)5.160$$
$$= 3526\ [\mathrm{Ws/m^2}]$$

The velocity of the wave group required for the calculation of the wave power affecting unit width for a water depth of $d = 10$ m and for $g = 9.81$ m/s^2 is obtained from Eq. (4) to be:

$$C_g = \sqrt{gd} = 9.91\ [\mathrm{m/s}]$$

In this case, for the unit width of wave, the wave power is found from Eq. (3) as follows:

$$\bar{P} = \frac{P}{b} = \bar{E}C_g = 3526 \times 9.91 = 34.943\ [\mathrm{kW/m}]$$

This means that the energy that will be delivered by a wave advancing in shallow water to a vertical object with a width of 1 m in 10 min will be: $E(b = 1\ \mathrm{m}) = \bar{P} \cdot 1/6$ [kW h]

The power obtained by Eq. (3) will drive the wave turbine and it will produce electrical energy. Losses will occur during the production of electrical energy E_T from wave power. The turbine efficiency, which determines these loses, takes various values according to the type of the wave turbine. As an example for this, the efficiency values of a wave turbine with 3 kW nominal powers working since 1990 in China can be given. It is reported that the turbine efficiency in this plant that uses wave energy to compress the air used for the production of electricity changes within the range of 10–40% [7]. In this study, the efficiency of the wave turbine was taken as 25% and it was assumed that the turbine would be in operation during 85% of its working period. The factory price of the offshore buoy wave turbine per unit nominal power was assumed to be 1000 €/kW, which is also valid for wind and water turbines. The expenses for the annual maintenance-repair cost of the wave turbine, its insurance expenses, its capital and overhead costs were assumed to constitute 12.69% of the factory price of the turbine [8,9]. Additionally, it was assumed that the life of the wave energy plant would be 20 years and the amount of electricity calculated in this study would remain the same every year. Having made these assumptions, unit price of the wave electricity can be calculated from Eq. (5):

$$p = (\text{Expenditure for 20 years})/(\text{Amount of produced energy for 20 years}) \tag{5}$$

3. Results

The number of measurements carried out at each 10-min time intervals for every month, the average wave energy values per unit sea surface and the average wave power values per unit width are presented in Table 5. The variation of the average wave power per unit width according to months is shown in Fig. 2.

Through the 52 560 power values evaluated at each 10 min during the measurement period, the annual amount of the wave energy that is delivered to a control

Table 5
Values of the wave energy and wave power calculated for the periods examined

The period examined	Number of measurement interval for 10-min periods	$\bar{E}_{\text{average}} = \gamma_{\text{sw}} \cdot \int_{0,2}^{3} S_{\zeta\zeta}(\omega)\, d\omega$ (Ws/m^2)	$\bar{P}_{\text{average}} = \frac{P}{b} = \bar{E}C_g$ (kW/m)
05.11.1998–05.12.1998	4320	1807.16	17.90
05.12.1998–05.01.1999	4464	2269.94	22.48
05.01.1999–05.02.1999	4464	2299.58	22.78
05.02.1999–05.03.1999	4032	4003.68	39.66
05.03.1999–05.04.1999	4464	1436.87	14.23
05.04.1999–05.05.1999	4320	722.95	7.16
05.05.1999–06.06.1999	4464	992.32	9.83
05.06.1999–05.07.1999	4320	890.84	8.82
05.07.1999–05.08.1999	4464	1097.61	10.87
05.08.1999–05.09.1999	4464	978.61	9.69
05.09.1999–05.10.1999	4320	1632.66	16.17
05.10.1999–05.11.1999	4464	1310.20	12.98

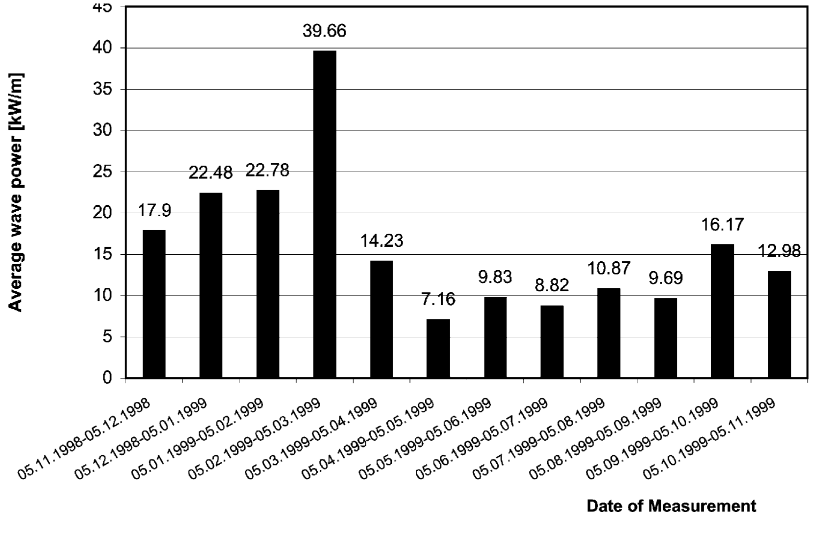

Fig. 2. Change of average wave power vs. months in Cesme.

Table 6
Economical analysis of the wave turbine with a width of 1 m in circumstances of Cesme

Factory cost of turbine (€)	Maintenance-repair, capital, overhead cost, insurance expenses (€)	Total expenditure for 20 years (€)	Amount of electrical energy produced for 20 years (kW h)	Unit cost of wave electricity (€/kW h)
15 000	(20)(1904) = 38 080	53 080	(20)(27616) = 552 320	0.096

surface with a width of 1 m, placed vertically across the propagation direction of the waves, is determined as 129 956.4 kW h. Similarly, after assessing 52 560 values collected at each 10-min time intervals, the average wave energy affecting unit sea surface area is found to be 1 497 820 Ws/m^2, and the annual average wave power affecting unit width is calculated as 14.84 kW/m. Under these circumstances, it will be advisable to use a wave turbine having 15 kW/m of nominal power for the production of electrical energy in Cesme. Assuming that the wave turbine efficiency will be 25% and that the turbine will be in operation during 85% of its working period, the amount of energy to be produced by using the wave energy plant comes out to be 27 616 kW h/year.

In case, when a turbine with a capacity of 15 kW/m is used for electricity production, the factory price of the wave turbine (that uses the energy of a wave with a width of 1 m) will become 15 000 €. The results of the cost analysis carried out on the basis of this price are given in Table 6.

4. Discussion and conclusion

In this study, it was indicated that more wave electricity could be produced in Cesme during the five months from October to the beginning of March than other months of the year. The fact that more wave electricity could be produced during winter months, when the energy demand increases, makes the utilization of wave energy even more attractive. In February, the wave energy in Cesme reaches its highest level. By analysing the monthly averages of the wave power values calculated for Cesme, it was determined that the average wave power varies between 7.16 and 39.66 kW/m.

Comparison of the values in Figs. 1 and 2 shows that the average wind velocity is found higher in October than in September, whereas the average wave power is determined less in October than in September. This result presents that average wind velocity values could lead to wrong previsions in the determination of wave power. In order to avoid such mistakes it is necessary to calculate wave power values separately at discrete time intervals, as done in this study. The average wind velocity value of a month only gives a general thought about the average wave power in that month.

In determining the nominal power values of the wave turbines, the present average wave power potential has the primary role. Utilization of wave turbines having

higher nominal power than the present average wave power potential causes most of the turbine power to be idle. This consequently increases the price of unit wave electricity. Using a wave turbine with a nominal power less than the present average wave power will affect the economy of wave electricity negatively. It will be reasonable that the wave turbines to be installed in Cesme, where the average wave power affecting unit width is 14.84 kW/m, will have a nominal power of 15 kW/m.

Other researches give values of the average wave power affecting unit width at various locations as follows: North Eastern Atlantic: 100 kW/m [10], Portugal Coasts: 5–26 kW/m [11], Canada: 0.6–101.6 kW/m [12], Southern Africa 10–14 kW/m [13] and China 0.7–4.5 kW/m [14]. After evaluating these data, it results that the region of Cesme, where the average wave power affecting unit width is found as 14.84 kW/m within the time of research, possesses the capacity to compete with other countries regarding the utilization of wave energy.

Assuming that electrical energy, which is bought around 0.061 €/kW h from the national electricity network, is obtained from the wave power in Cesme and sold to the consumer without any losses, it will cost around 0.097 €/kW h. This means that wave electricity is currently not economical for locations where city network connection is available. However, fossil fuels are going to be depleted in the near future. For this reason, it can be expected that the prices of these fuels will increase, and the unit price of electricity to be obtained by using fossil fuels will be raised. Through accelerating researches in the area of wave mechanics and wave energy, the unit price of electricity to be produced from wave power can decrease so that wave electricity under these circumstances will become economical in the very near future.

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